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Matched filter stochastic background characterization for hyperspectral target detection

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ABSTRACT

Algorithms exploiting hyperspectral imagery for target detection have continually evolved to provide improved detection results. Adaptive matched filters can be used to locate spectral targets by modeling scene background as either structured (geometric) with a set of endmembers (basis vectors) or as unstructured (stochastic) with a covariance or correlation matrix. These matrices are often calculated using all available pixels in a data set. In unstructured background research, various techniques for improving over the scene-wide method have been developed, each involving either the removal of target signatures from the background model or the segmenting of image data into spatial or spectral subsets. Each of these methods increase the detection signal to background ratio (SBR) and the multivariate normality (MVN) of the data from which background statistics are calculated, thus increasing separation between target and non-target species in the matched filter detection statistic and ultimately improving thresholded target detection results. Such techniques for improved background characterization are widely practiced but not well documented or compared. This paper provides a review and comparison of methods in target exclusion, spatial subsetting, and spectral pre-clustering using preliminary matched filter detection results from a larger study. The analysis provides insight into the merit of employing unstructured background characterization techniques, as well as the limitations for their practical application.

Keywords: Hyperspectral, background characterization, matched filters, covariance

1. INTRODUCTION

Hyperspectral imagery (HSI) may be defined as imagery taken over many (usually more than one hundred) spectrally contiguous and spatially co-registered bands. Target detection exploitation of HSI attempts to locate pixels containing a target material of known spectral composition in a scene. The adaptive matched filter is a type of detector that models and suppresses an unstructured background characterized by the first and second order statistics (mean and covariance matrix) of a set of background pixels. Much of the work to improve matched filter performance has focused on improved scaling of detector results in order to increase separation between target detects and false alarms. Another and perhaps more fruitful approach to improved detection results is to improve the model of background, thus increasing the suppression of unwanted signal and creating greater separation between target detects and false alarms before scaling. Based on this concept, several methods for calculating background statistics have been developed in the field which are reported to improve detection results for specific targets, detectors, and HSI data sets [1] [2] [3]. Each of these methods takes cues from the imagery to establish a rationale for selecting which data is to be included in the estimation of background statistics. Establishing this rationale to model scene background and selecting a mathematical technique to formulate background statistics are together called the characterization of background. There are three factors to consider when attempting to improve matched filter background characterization. First and foremost is identifying the source of the signal interfering with the target. This serves two purposes: to suppress the spectra mixing with subpixel targets and to suppress the returns on target-like non-target species (likely false alarms). The second consideration is to ensure that no target signal is present in the background model, as even small amounts of target can be shown to dramatically alter background statistics. Third is to attempt, as much as possible, to seed the second moment with data that will adhere to the assumption of multivariate normality inherent in the traditional matched filter detector. This paper will discuss several methods of spatial and spectral subsetting and target exclusion that attempt to raise the detection signal to background ratio (SBR) and will introduce a new method combining these concepts.

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2. METHODOLOGY

2.1 Matched filter detection

A variety of matched filters have been developed which use the Mahalanobis (or statistical) distance between a known target spectrum and a scene pixel as the primary measure of target presence. This simple matrix multiplication can be expressed

$$T = (d - \mu)^T \Sigma^{-1} (x - \mu) \quad (1)$$

where d is the target spectrum, μ and Σ are the mean and covariance matrix for the background distribution, x is the scene pixel being tested (the detection pixel), and superscript T denotes the matrix transpose. Noting that the covariance matrix is inverted, we see that equation 1 is a spectral matched filter measure of signal divided by the statistical model of background. Thus the detection statistic T may also be considered a measure of signal to background ratio (SBR) [1]. In order to increase distance between target and non-target returns in the detection statistic, matched filters have been derived either by minimizing the total energy of the filter output by the Constrained Energy Minimization (CEM) technique [4], or by maximizing the cost function [2]. From the cost function derivation a family of matched filters has been developed to include the Generalized Likelihood Ratio Test (GLRT) detector, the Adaptive Coherence Estimator (ACE) detector, and the Adaptive Matched Filter (AMF), which all scale the statistical distance differently to achieve improved results. Only the GLRT detector, which can be expressed

$$T_{GLRT} = \frac{(d^T \Sigma^{-1} x)^2}{(d^T \Sigma^{-1} d)(1 + x^T \Sigma^{-1} x)} \quad (2)$$

for mean centered data, will be used for this study to allow for level comparison of background characterization techniques. When using any of these detectors, it is important to note their underlying assumptions. First, the background is homogeneous and exhibits multivariate Gaussian behavior. Second, the background spectrum interfering with the target signature has the same covariance as the background training pixels. Third, the spectra of the target and background must combine in an additive manner [2].

2.2 Spatial subsetting

The first and perhaps most obvious method of improving on background characterization with scene-wide statistics is to manually select a spatial subset of the scene to represent the background. If the user has some knowledge of general target location, the background subset may be selected from a region of the scene imaged prior to the sensor reaching the target area. This "target approach" method can be used both to exclude targets and to achieve greater multivariate normality (MVN). The drawback of the target approach method is that it is difficult to decide which background best represents the signal mixing with subpixel targets, or that which may cause the most false alarms.

Another method of spatial subsetting, which is aimed at detecting the signal interfering with subpixel targets as well as increasing MVN of the background, is the RX algorithm [3]. The original algorithm implemented a combination of spatial and spectral matched filters, defining the spectral matched filter background with a sliding window to recalculate local background statistics for each pixel. According to the construction of the algorithm, the mean of the background can be calculated within a windowed subset of the data and the more slowly varying covariance can be calculated from a larger target-free subset and approximated by a diagonal matrix. The third moment (approaching zero) was used to approximate the normality of the spatial subset. Minimizing skew in this way was assumed to "create a distribution which is as close to Gaussian as possible" [3].

Limiting target influence on the sliding window characterization of background is an important consideration for RX because the smaller the window size, the greater the impact just a few target pixels will have on background statistics. We will examine two ways in which targets may be excluded from the sliding window background, which can be applied alone or in combination. First, the background window can be constructed with a central exclusion region spanning a distance twice the approximate size of the target, as depicted in Figure 1(a). Second, a prescreening step

employing a loosely thresholded simple algorithm like Spectral Angle Mapper (SAM) which can exclude possible target species before RX detection, as shown in Figure 1(b). This prescreening is drawing a spectral distinction between species similar to and different from the target. The same concept can be extended to pre-cluster the image and spectrally subset the data to improve background characterization, as discussed in the next section.

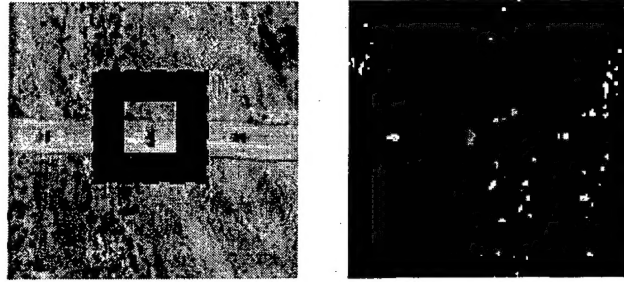


Figure 1. (a) RX background window (in gray) demonstrating the exclusion of the central vehicle target, and (b) the decision map for SAM target exclusion prescreening where white pixels are excluded from the sliding gray background.

2.3 Spectral subsetting

Many new target detection algorithms have sought to exploit methods of HSI classification to gain advantage in the matched filter detection problem. The premise for improved detection results through pre-clustering (spectrally subsetting) is achieving greater SBR by only comparing the target to pixels in a single class. The distribution of pixels within a class is intuitively more normal than intra-class mixtures, and a single class may be able to suppress the source of prominent false alarms in a scene. However, selecting a method of combining detection results using pre-clustered data can be complicated for hard target detection. The inclusion of target pixels in the background is also a problematic issue in pre-clustering. While the class covariance that maximizes SBR may not contain any target, at least one class close to the target will include target pixels. In order to use the class containing target species as background, the target pixels must be excluded from the class. Some techniques aimed at accomplishing pre-clustering target exclusion will be discussed later. First, we will examine a couple of classification algorithms that may be used for pre-clustering.

K-Means is a simple and commonly used unsupervised image classification method which requires the user only to specify the number of classes. Random class means are generated and each image pixel is assigned to a class by calculating a minimum distance to the mean. New class means are calculated based on the pixel assignments and the process is repeated until the means stop changing by a thresholded amount [5]. The matched filter can be adapted to incorporate results from a K-Means clustering, a method that has been shown to increase the performance of several forms of the adaptive matched filter when applied to HSI for plume detection [1]. For the GLRT detector, the adaptation takes the form

$$T_{GLRT}^k = \frac{(d^T \Sigma_k^{-1} x)^2}{(d^T \Sigma_k^{-1} d)(1 + x^T \Sigma_k^{-1} x)} \quad (3)$$

where k is the class number and values are mean subtracted using class means. The K-Means pre-clustering technique has also been used to improve anomaly detection results in multispectral IR imagery [6]. In both of these studies, it was noted that improvements in the method of classification will lead to improved detection results.

Stochastic Expectation Maximization (SEM) is another classification technique which considers not only first order (mean), but also second order (covariance) information when assigning pixels to a class. SEM is an unsupervised form of the supervised Gaussian Maximum Likelihood (GML) classification technique. The process is initialized by random assignment of pixels or from the results of a previous classification. Classes are modeled as normal distributions, combining additively to form the image by the expression

$$p(x) = \sum_{i=1}^K p(i) \left[\frac{1}{(2\pi)^{-t/2} |\Sigma_i|^{1/2}} e^{-\frac{1}{2}[(x-\mu_i)^T \Sigma_i^{-1} (x-\mu_i)]} \right] \quad (4)$$

where K is the number of classes and $p(i)$ is the probability of each class existing. The class statistics may be estimated from the distributions in $p(x)$, which exist in the data. The probability of class m existing in the next iteration can then be calculated by

$$P_m^{n+1}(i) = \frac{N_m^n}{N} \quad (5)$$

which must exceed the user defined threshold for minimum class size. The probability of each class existing $p(x|i)$ in the next iteration can then be estimated from the results, leading to an estimated *a posteriori* probability of each class, which can be expressed

$$P_m^{n+1}(i|x) = \frac{P_m^{n+1}(i) P_m^{n+1}(x|i)}{\sum_{q=1}^M P_q^{n+1}(i) P_q^{n+1}(x|i)} \quad (6)$$

where M is the user defined maximum number of classes [7]. Pixels are reclassified based on these probabilities and the new mean, covariance, and $p(i)$ values are calculated for each class. These values then seed the next iteration and the process continues until a convergence criterion has been satisfied. Incorporating second order statistics into the classification process allows the algorithm to consider spectral shape of a class, leading to more accurate classification and more normal class statistics within the classified image. SEM has been used in combination with RX to improve detection results through fusion [8]. Fusion rules for combining results, including model selection, AND/OR, and joint-density, were employed to create decision boundaries encompassing thresholds for each algorithm and for a normality metric, resulting in the reduction of false alarms by between 0.25 and 2.0 orders of magnitude.

2.4 Combined spectral and spatial subsetting with Adaptive RX

A new method of background characterization called Adaptive RX (ARX) uses the results of classification and incorporates the concept of the RX sliding window. Like RX, the ARX algorithm assumes that the best background for a target comes from the surrounding pixels. A limitation of the RX sliding window is that the size of the window must be small enough to capture the statistics of only the local neighbors of the detection pixel, but large enough to allow for sample sizes needed for well determined statistics. If the number of pixels in a window is less than the number of bands, the covariance matrix will be singular and cannot be traditionally inverted, and if the number of pixels is only a few times the number of bands, the matrix is usually highly elliptical and errors resulting from its use can be significant [9]. Classification can be used to overcome the problems with underdetermined statistics while preserving the ability of RX to capture the immediate surroundings of the detection pixel. By polling the pixels neighboring the detection pixel and outside of an exclusion region, we can construct fractions of the detection pixel surroundings that originate from each class. We can then form a linear mixture of the k class statistics to form a single class mean and covariance matrix which characterize the local background with well determined statistics. Figure 2 depicts an ARX window for a single detection window and equation 7 gives the expression for the resulting linear statistical mixtures,

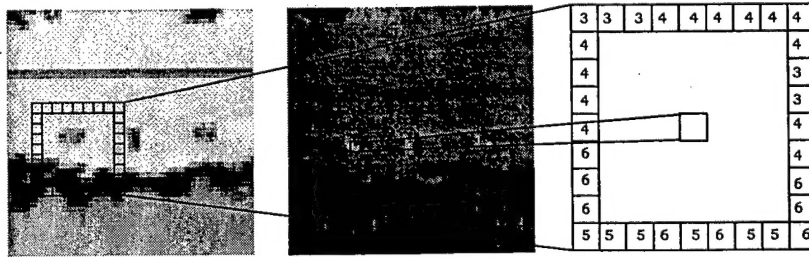


Figure 2. Adaptive RX representation where numbers in the torus represent class identifications.

$$\Sigma = \sum_{i=1}^k \alpha_i \Sigma_i \quad \mu = \sum_{i=1}^k \alpha_i \mu_i \quad (7)$$

where α_i is the fraction of class i contained in the pixels neighboring the detection pixel. Pixels from the class map are polled to establish the α ratios and the resulting class statistics are used in the matched filter applied to the central detection pixel. The background for each detection pixel unique and matched to its surrounding, but runtime is greatly reduced compared to RX. The algorithm also employs a technique to improve class statistics, which are usually derived directly from the class map. Understanding that each pixel in the scene has been forced into a distribution to which it may not belong, improvements may be made by excluding the outliers of each distribution and recalculating class statistics. If the target happens to reside in the tail of the distribution, it will be excluded; if not, targets can be excluded using a loosely thresholded SAM. In either case, statistical distance exclusion (SDE) eliminates the extremity of each class and essentially cuts off part of the heavy tail of the distribution, thereby increasing the MVN of the data seeding the statistics for matched filter detection. Figure 3 shows the distribution of a single SEM-generated class, first with no exclusion, then with target pixels (marked +) excluded by SAM prescreening, and finally with the heavy tail reduced by SDE (pixels marked X).

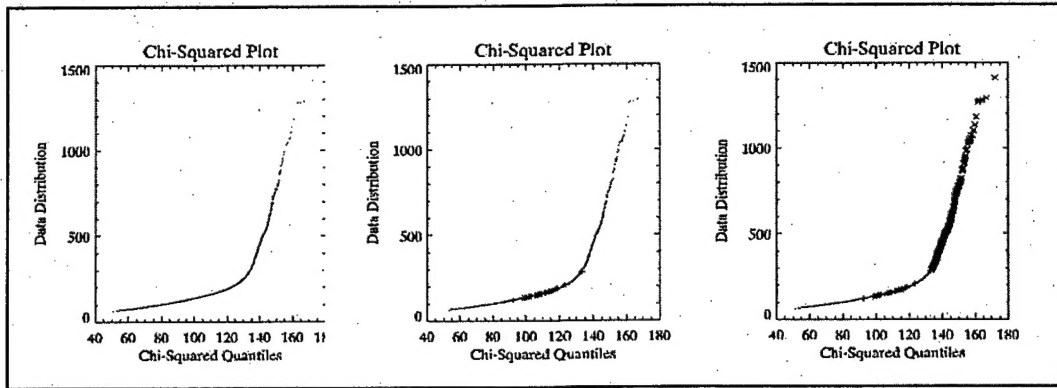


Figure 3. Chi-Squared MVN plots showing pixels excluded by SDE and SAM prescreening.

2.5 Evaluation metrics

Detection results are commonly represented by a receiver operator characteristic (ROC) curve comparing probability of detect to probability of false alarm. For targets with very few pixels, the error in calculating these probabilities can be preventative. We will therefore construct ROC curves with a rate of detection and false alarm, generated by simply counting the false alarm occurrences as each target pixel is detected. This will allow for a comparison of detection results without calculating probabilities and making a general statement of algorithm performance. For more direct comparison, we can reduce the ROC curve to a single numerical value by taking an average false alarm rate (AFAR) [10]. This representation of the area above the ROC curve is a good indication of detection performance in finding all target pixels. To capture detection performance at low false alarm rates, a partial AFAR can be calculated as the area above the curve to a certain level of detection.

There are a number of available metrics to test a data subset for adherence to the multivariate normality assumption. MVN tests can generally be separated into four categories: graphical examination with correlation coefficients, tests for goodness-of-fit, skewness and kurtosis tests, and consistent procedures based on the empirical characteristic function [11]. For this data, we will use a goodness-of-fit (GoF) metric with the Chi-Squared MVN test. For this test the rank ordered distribution of the statistical distance from the mean (d^2) is plotted versus the expected value given by the chi-squared distribution quantiles (χ^2) and the chi-squared GoF is measured by

$$\chi_{GoF}^2 = \frac{1}{N} \sum_{i=1}^N \frac{(d_i^2 - \chi_i^2)^2}{\chi_i^2} \quad (8)$$

where N is the number of pixels in the subset [12]. While observation of the chi-squared plot gives insight into the shape of the distribution, the GoF measure gives a single numerical value allowing for a rough comparison between distributions.

3. DATA

To illustrate the performance of different background characterization techniques, we will use Hydice data cubes from the Forest Radiance I and Desert Radiance II collect. Several data cubes from this experiment were analyzed by MIT Lincoln Laboratories for the purpose of exploitation algorithm development. Figure 4 shows a single band from each of the images with the target locations and target approach background regions indicated.

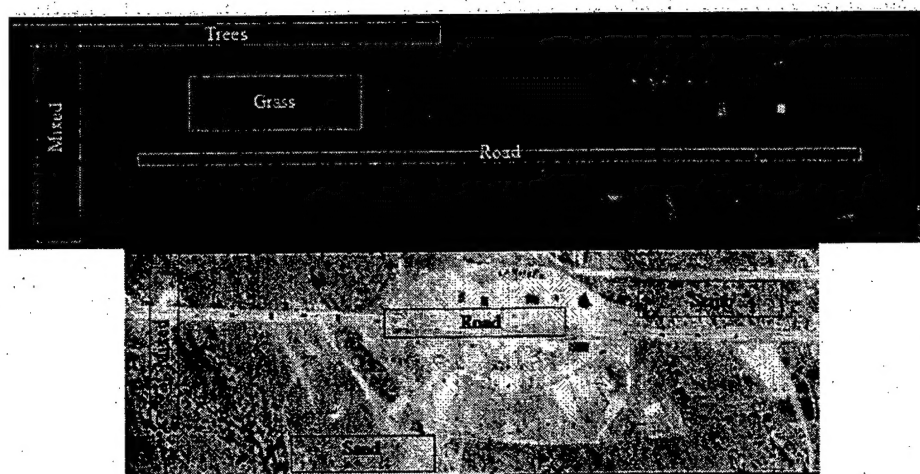


Figure 4. Forest and Desert scene with targets and background subsets indicated.

The ground truth spectra, target location maps and some class maps used to perform this analysis were provided in the data set. For simplicity, we will look at a single target that appears in a forest and desert scene. There are 45 full pixels, 28 subpixels, and 55 shadow pixels for a total of 128 target pixels in the forest scene, and 115 full pixels, 47 subpixels, and 73 shadow pixels for a total of 235 target pixels in the desert scene. This number and variety of target pixels will allow for a range of detection performance for each background characterization technique. Analysis of detection performance within each of these categories (i.e. finding the best background for subpixel targets only) is made possible by this data, but will not be presented as part of this study.

4. RESULTS

4.1 Target approach results

Four target approach regions outlined in figure 4 above containing were selected from the data sets in a manner similar to previous studies [2]. There were 18K pixels selected for each background in the forest scene and 10K pixels selected for each background in the desert scene. Using a general knowledge of target location, the backgrounds can confidently be presumed target free. Detection results using the GLRT detector with each of these backgrounds as well as the scene-wide backgrounds are shown in Figure 5. The AFAR reported below, and for all subsequent figures, is a 95% partial AFAR, excluding the last 5% of pixels detected in order to capture detection performance at lower false alarm rates. Note from the chi-squared GoF plots that each of the subsets exhibits far greater MVN than the full scene background.

For this target, the mixed background performed well in the desert image even though the class was the least multivariate normal of the subsets. This illustrates the balance between maximizing SBR and exhibiting MVN, and indicates that the full scene background performed poorly, not because the type of spectra it contained were not suited to maximize SBR, but because the collection of pixels in the full scene strayed far enough from MVN to confound the

results. Noting that the desert road proved to be a worse background than full scene, we see that it is possible to select a background more normal than the full scene that fails to match (and therefore suppress) the interfering signal.

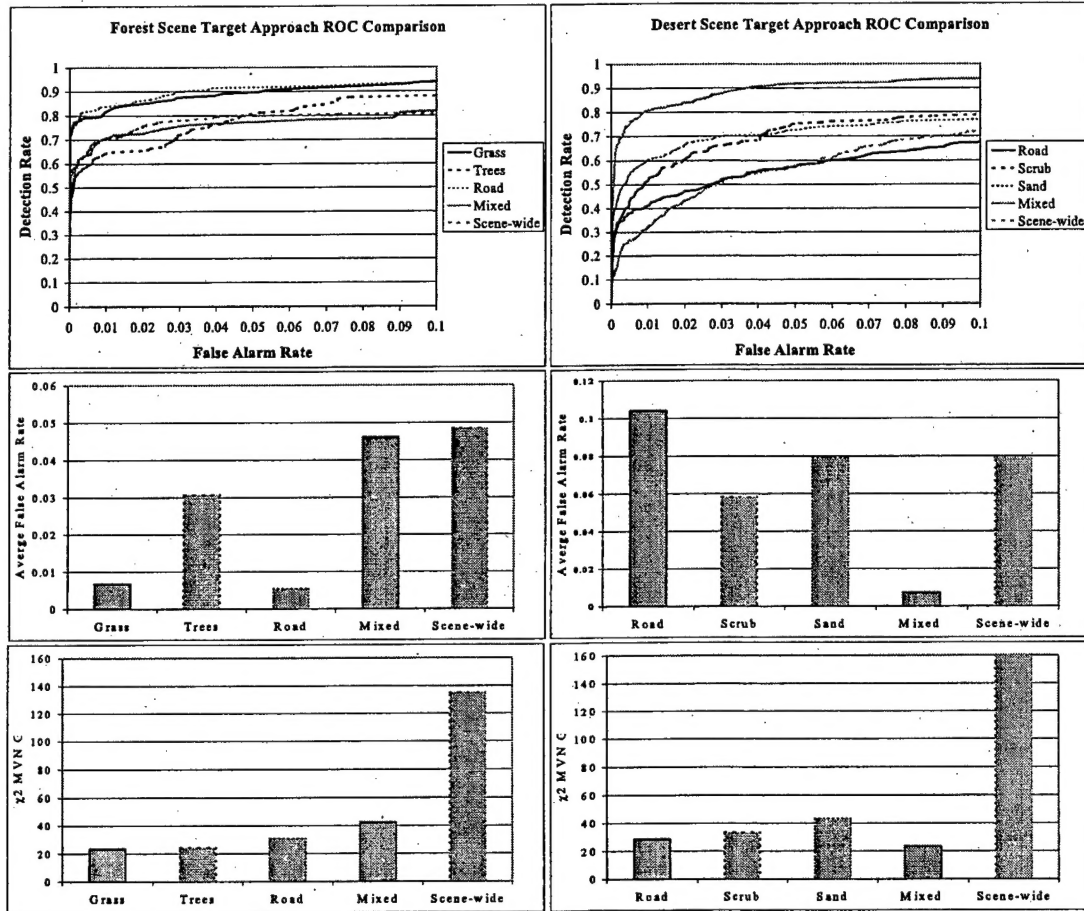


Figure 5. GLRT detection results using target approach and full scene backgrounds.

4.2 Target influence demonstration

The target approach subsets lend themselves well to a simple study of the influence of target species on the background covariance. By including target pixels from elsewhere in the scene into the target free backgrounds, we can observe the changes in background statistics that would occur had we mistakenly included them. To quantify this change we can decompose the covariance matrix by the generalized eigenvalue problem

$$\Sigma = U^T \Lambda U \quad (9)$$

where U is an orthogonal matrix with columns containing the eigenvectors and Λ is a diagonal matrix containing the eigenvalues along the diagonal. While addition of a few target pixels in a large background may not change the overall variability in the covariance matrix, the shape of the matrix (which is of great importance for spectral matched filtering) will change significantly with only a few spectrally distinct target pixels. Changes in the shape of the covariance matrix manifest through changes in the ordered eigenvectors. Figure 6 shows the spectral angle between each of the first ten eigenvectors for the addition of six target pixels. Note that with the addition of just a few targets, the sixth eigenvector changes significantly. To see how this impacts detection, the figure also shows the GLRT return on a single target pixel compared to the maximum background return for up to ten target pixels included in the background. At zero pixels

included, the target return is above the maximum background and can therefore be found without false alarm. By seven target pixels included (in a background of 18K), the target return falls below the maximum background.

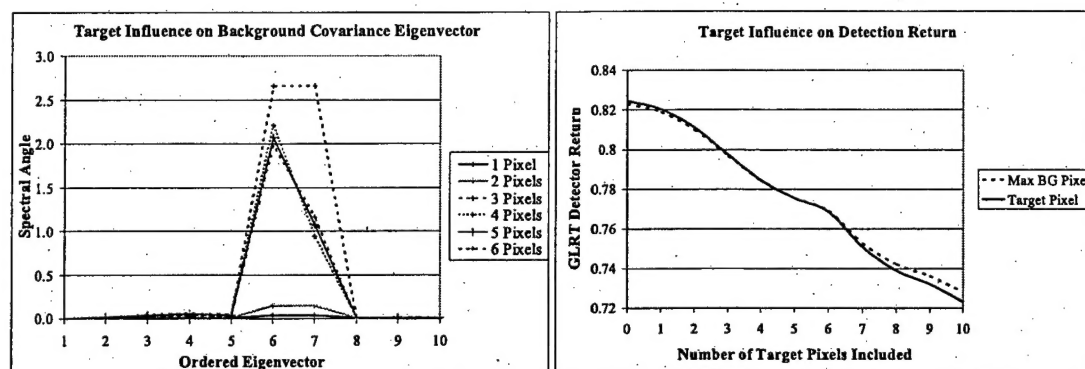


Figure 6. Spectral angle between eigenvectors and GLRT return for various levels of target inclusion in background.

4.3 RX sliding window results

Another example of the importance of target exclusion can be found when selecting the parameters of the RX algorithm. The target vehicles in the forest scene are approximately ten pixels on a side and spaced thirty pixels apart. It is important to select correct sizes for the sliding window to prevent both the inclusion of pixels from neighboring targets (cross contamination) and from the target being detected (self contamination). Figure 7 shows the setup and results for the RX sliding window with correctly selected background and exclusion windows, as well as the cross- and self-contaminated cases. The results are labeled $RX(i,j)$ by the pixel size of the exterior (i) and the interior (j) windows respectively. From the figure, it is clear that the target-free background, $RX(33,19)$, outperforms the background which sporadically picks up target pixels from nearby target vehicles, $RX(47,35)$. The properly sized sliding window also outperforms the background which steadily includes pixels from the vehicle being detected, $RX(31,5)$.

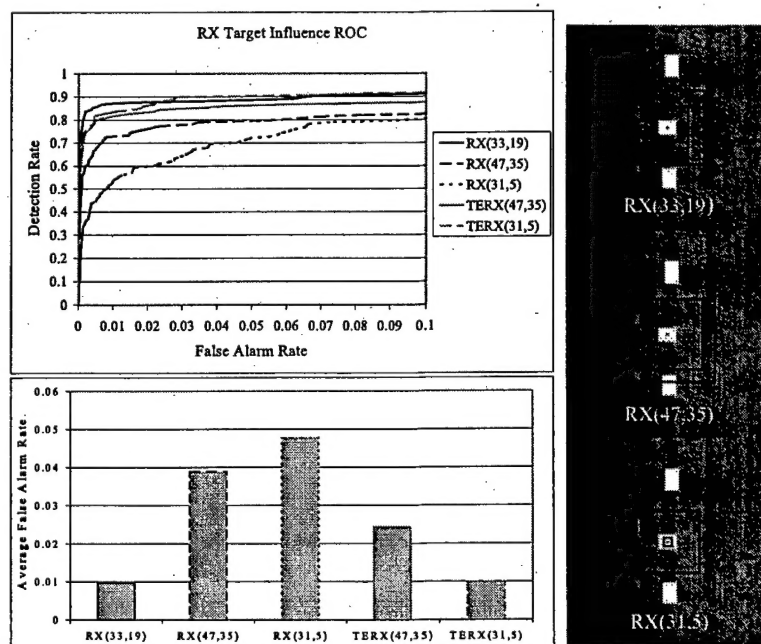


Figure 7. Results for RX sliding window detection for uncontaminated, cross-contaminated, and self-contaminated cases, as well as target excluded results for the poorly formed cases.

Also shown are the results of detection with the contaminated window sizes prescreened with a loosely thresholded SAM. The SAM detection statistic was thresholded to exclude 300 pixels, roughly twice the number of assumed target pixels in the scene. The SAM prescreened target exclusion RX (TERX) elevates results of the poorly selected window sizes nearly to the level of the correctly selected case.

Freedom to select reasonably sized RX windows without concern for target contamination is desirable, recalling that the size of the RX window will also influence the stability of the background statistics. For these results an attempt was made to keep background size ($i^2 - j^2$) consistent. Future studies will include analysis of the influence of total background size on detection performance. A final consideration for the RX approach is the runtime involved when computing a unique background for each detection pixel. The sliding window covariance approach is a computationally expensive method of background characterization.

4.4 Pre-clustering results

The next step is to compare the results of pre-clustering for different types of classification algorithms. Five classes in the desert scene and six classes in the forest scene were identified by K-Means and SEM classification and the results were used to develop background statistics to seed the GLRT detector. Figure 8 shows the forest scene detection results for each class background for both classification algorithms. As expected, the MVN of the classes is improved by the SEM algorithm and the results of detection with SEM class backgrounds are better than K-Means for most classes. It is interesting to compare these results with those in Figure 5, where the K-Means selection of trees performs similarly to the hand-selected trees background. In contrast, the grass background was divided by unsupervised classification into two types with differing performance as backgrounds. The hand-selected grass background performed in between the two grass classes, indicating a mixture of light and dark grass in the target approach region. The best performing background was the dirt class, pieced together from spatially scattered pixels which are impractical if not impossible to gather by hand. This class outperformed the best target approach region, demonstrating the utility of pre-clustering as a background characterization technique.

Figure 9 shows the desert scene detection results, which reveal greater improvement of SEM over K-Means, and demonstrate the effect of target presence in a cluster. The detection improvements are clear with the SEM medium ground class finding every target pixel within a 0.07 false alarm rate. K-Means classified the targets as part of the brush class (nearest in Euclidean distance), while SEM included them in the light ground class (nearest in statistical distance). Detection results using these backgrounds were heavily impacted by target presence, a fact which leads to a prime difficulty in the practical implementation of this method. Blindly selecting a single class to represent background is non-trivial. In order to use the closest class as a background, target pixels need to be excluded, either by SAM prescreening or by setting a statistical distance exclusion threshold. It was confirmed in processing that most false alarms occur within the class closest in statistical distance to the target, and when that class was used as background the false alarms were evenly distributed throughout the image. The second closest class becomes the best background, confining false alarms to a single class, and minimizing the return of other classes. Intuitively, the best approach would be to exclude target pixels from the cluster in which they reside, preventing them from being suppressed as background and causing them to stand above false alarms in all other classes. This seems to enter a circular argument, but may be the key to the best automated pre-clustering background characterization technique.

4.5 Adaptive RX results

Combining the RX sliding window and pre-clustering techniques described above, the Adaptive RX technique eliminates the need to select an ideal window size or choose from a set of classes. Figure 10 shows the results of ARX for the forest scene, compared with the best and worst performing target approach, RX, and pre-clustering background characterization methods. These preliminary results indicate that ARX may outperform other background characterization techniques if poor assumptions have been made during processing, but does not match the intelligent analyst in detection capability. A plausible cause for this lies in the assumption that the best background for a target pixel can be derived from its immediate surroundings. This may be the case for subpixel targets, where the background should model the source of interference mixing with the target signal within the pixel. However, for fully resolved pixels, the best background may be that which suppress the source of false alarms from elsewhere in the image; and as we see in the pre-clustering experiment, the road on which the target rests is not ideal for suppressing false alarms.

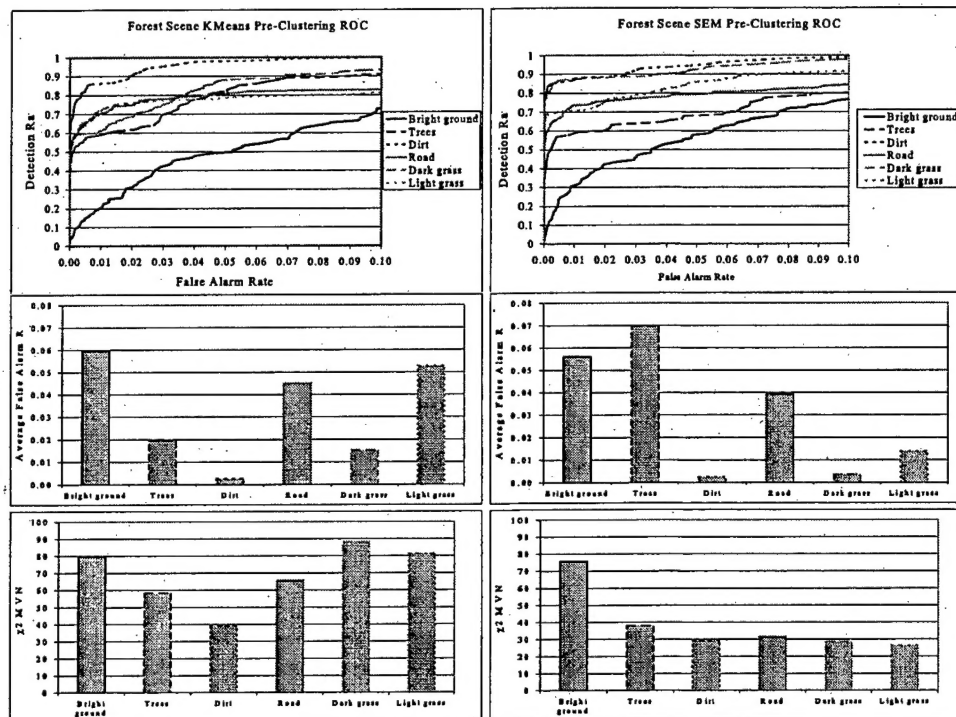


Figure 8. Pre-clustering detection results for the forest scene.

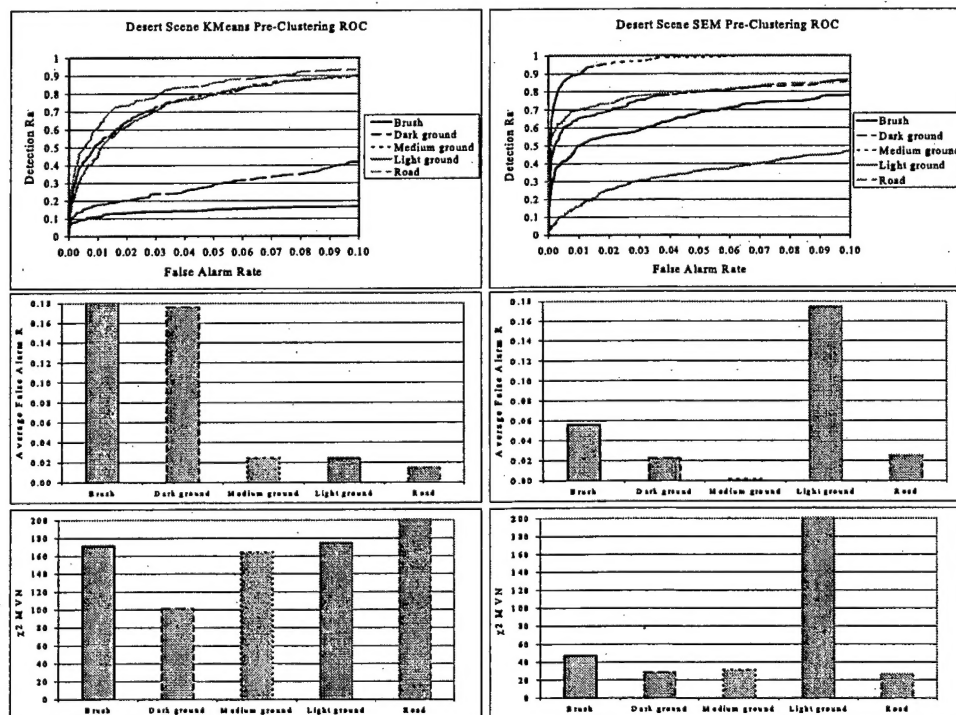


Figure 9. Pre-clustering detection results for the desert scene.

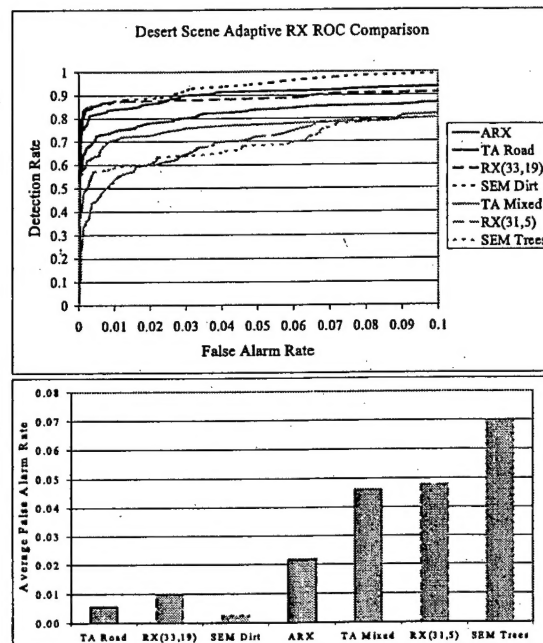


Figure 10. Adaptive RX results compared to best performance of other techniques.

5. CONCLUSIONS

We have reviewed several techniques for background characterization involving the spectral and spatial subsetting of data in an attempt to improve the separation of target from background in spectral matched filter detection returns. The utility of the target approach technique was demonstrated by showing that detection results can be improved by hand-selecting a small background versus using every pixel in the scene. This technique leaves the decision to the analyst as to which pixels best represent background for a given target. We demonstrated the importance of target exclusion by observing changes in the shape of covariance matrixes with the addition of only a few target pixels. Spatial and spectral techniques for target exclusion were investigated using the sliding window background of the RX algorithm, revealing the importance of carefully selecting window parameters. Comparing the results of two pre-clustering techniques, K-Means and SEM, we showed that SEM classification improved the multivariate normality for each class and the detection results for most background clusters. The presence of target species in pre-clustered backgrounds is problematic, and selection of the best background class is easily confounded by contamination. We introduced a new method, called Adaptive RX (ARX) which incorporates pre-clustering statistics into the sliding-window background characterization concept. Preliminary results for the unsupervised ARX method indicate that it may improve detection results if less than ideal assumption were made during target approach, RX, or pre-clustering background characterization, but does not outperform correctly characterized backgrounds for these methods.

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